
REPORT No. 282

**THE
PERFORMANCE OF SEVERAL COMBUSTION CHAMBERS
DESIGNED FOR AIRCRAFT OIL ENGINES**

**By WILLIAM F. JOACHIM and CARLTON KEMPER
Langley Memorial Aeronautical Laboratory**

REPORT No. 282

THE PERFORMANCE OF SEVERAL COMBUSTION CHAMBERS DESIGNED FOR AIRCRAFT OIL ENGINES

By WILLIAM F. JOACHIM and CARLTON KEMPER

SUMMARY

Several investigations have been made on single-cylinder test engines at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics to determine the performance characteristics of four types of combustion chambers designed for aircraft oil engines. Two of the combustion chambers studied were bulb-type precombustion chambers, the connecting orifice of one having been designed to produce high turbulence by tangential air flow in both the precombustion chamber and the cylinder. The other two were integral combustion chambers, one being dome-shaped and the other pent-roof shaped. The injection systems used included cam and eccentric driven fuel pumps, and diaphragm and spring-loaded fuel-injection valves. A diaphragm-type maximum cylinder pressure indicator was used in part of these investigations with which the cylinder pressures were controlled to definite values. The performance of the engines when equipped with each of the combustion chambers is discussed. The data presented show the performance for speeds from 600 to 1,800 R. P. M.

The results obtained indicate that aircraft-type oil engines with suitably designed combustion chambers and fuel-injection systems may be operated at speeds around 1,800 R. P. M. without encountering excessive explosion pressures. At a speed of 1,600 R. P. M. and with a fuel quantity giving 15 per cent excess air in the cylinder, a maximum I. M. E. P. of 119 pounds per square inch was obtained with a fuel consumption of 0.48 pound per I. HP. per hour. The maximum cylinder pressure was 740 pounds per square inch. A minimum fuel consumption of 0.26 pound per I. HP. per hour at an I. M. E. P. of 52 pounds per square inch and 1,600 R. P. M. was obtained with a cylinder head having a bulb-type precombustion chamber. The maximum cylinder pressure was 560 pounds per square inch.

It is concluded that an increase in the specific power output of the high-speed aircraft oil engine depends upon the ability to obtain higher mean effective pressures and an improvement in the mechanical efficiency of the engine. The best performance for the tests reported was obtained with a bulb-type combustion chamber designed to give a high degree of turbulence within the bulb and cylinder.

INTRODUCTION

The design of combustion chambers to meet the fundamental requirements of high-speed, fuel-injection engines is a part of the National Advisory Committee for Aeronautics research program for the development of the aircraft oil engine.

The essential requirements to be met in the design of combustion chambers for high-speed oil engines are, first, the fuel spray must be completely distributed throughout the combustion chamber; second, the degree of cylinder air turbulence must be sufficient to produce complete burning of the fuel in the short time available; and, third, the ignition and combustion of the fuel must take place early enough in the power stroke to give high mean effective pressures without excessive explosion pressures. (References 1 and 2.) Since November, 1924, reliable data have been obtained as to the behavior of fuel sprays when injected into gases under pressure.

The National Advisory Committee for Aeronautics, in its investigation of oil sprays for fuel-injection engines, has recorded the start, development, and cut-off of sprays by means of high-speed moving pictures. (References 2, 3, and 4.) The data obtained from the several researches conducted thus far enable the combustion chamber to be more efficiently designed to fit the fuel spray selected.

Other requirements for fuel-injection engine combustion chambers are the same as those for any type of engine. Thus, the combustion chamber must be strong enough to withstand the explosion pressures. It should also give a uniform dissipation of heat and prevent large temperature differences which may lead to cracking of the cylinder head. Particular attention should be given to the location of the inlet valve to provide an unobstructed flow of air into the engine cylinder.

If the oil-injection engine is to compete with present-day carburetor engines for aircraft, it is necessary that the weight per brake horsepower be reduced to approximately 3 pounds. This reduction in weight may be brought about by increasing the speed of the oil engine from the relatively slow speeds of around 300 R. P. M. to a speed of 1,800 R. P. M. The attainment of this engine speed, if good combustion and fuel economy with low maximum cylinder pressures are to be maintained, is complicated, however, by the problems of fuel injection, the degree of atomization, spray velocity, turbulence, and the short time available for vaporization and ignition of the fuel. For a four-stroke cycle engine running at 1,800 R. P. M. and having an injection interval of 30°, the corresponding injection time is approximately 0.003 second. The lag of autoignition, as determined for slow and medium speed engines, depends upon the compression ratio, the combustion chamber, and the fuel-injection system. An average value may be taken as approximately 0.020 second. If the performance of the fuel-injection engine is to be increased at high engine speeds without excessive cylinder pressures, it is necessary that the time lag of autoignition of the fuel be decreased or the entire fuel charge may be injected into the cylinder before ignition occurs. Under these conditions combustion will take place at practically constant volume, with resulting explosion pressures which may exceed 1,600 pounds per square inch.

In order to avoid these excessive explosion pressures, many engine designers use a pre-combustion chamber in which the small volume of air permits only partial combustion of the fuel charge, further combustion of the fuel taking place in the cylinder proper. The connecting orifice between the two chambers is usually designed to meter the products of the partial combustion in the precombustion chamber to obtain practically constant pressure combustion in the cylinder.

The use of the connecting orifice between the bulb and the cylinder results, at higher engine speeds, in the following losses: First, a friction or pumping loss due to forcing the gases through the orifice at high velocity; second, a loss in pressure on the piston caused by the lag of the gas pressure; and third, an increase in the heat loss to the jacket water due to the scrubbing action of the gases. These losses may be more than compensated for by the increase in combustion efficiency obtained by the higher degree of turbulence produced by the orifice.

DESCRIPTION OF APPARATUS

TEST ENGINES

The performance of a given design of combustion chamber is determined at the Langley Memorial Aeronautical Laboratory by tests made with single-cylinder test engines having a 5-inch bore and a 7-inch stroke. (References 5 and 6.) The engines are coupled to 50-75 horsepower electric cradle-type dynamometers. The cylinder heads are bolted to special steel cylinders which are bolted to the engine crankcase. Standard aircraft engine valves, pistons, and connecting rods are used. Arrangements are provided to maintain fuel, oil, and water temperatures at constant values. For the tests reported the water-outlet temperature and oil temperature were maintained, respectively, at 140° and 120° F. A general view of the single-cylinder Liberty test engine is shown in Figure 1.

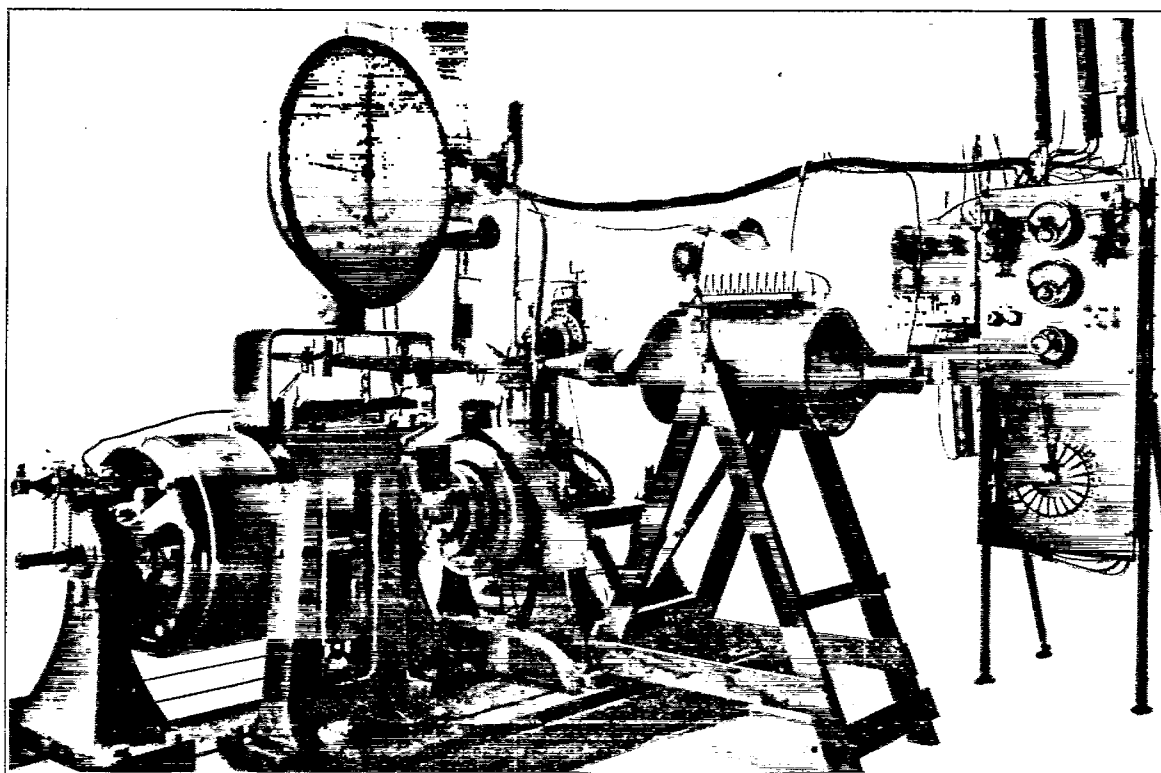


FIG. 1.—Arrangement of Liberty type test engine and apparatus

INJECTION SYSTEM

The fuel-injection systems for the tests reported on cylinder heads designated as Nos. 1 and 3 comprised a primary gear pump supplying oil at 90 pounds per square inch pressure to a cam-actuated impact-type injection pump, and an automatic fuel-injection valve. (Reference 6.) The opening pressure and design of the fuel-injection valve control the pressure at which the fuel is delivered by the injection pump. The type of injection valve determines the necessary opening pressure for maximum efficiency. For the investigation of cylinder head No. 3 a spring-loaded injection valve was used having a static opening pressure of 6,000 pounds per square inch. The design of this injection valve limits the maximum injection pressure to approximately 6,000 pounds per square inch.

CYLINDER HEAD NO. 1

The first combustion chamber designed for fuel-injection work is shown in Figure 2. The design was recommended for test because of its simple construction and uniform shape. Due to the Liberty type of valve mechanism used with this cylinder head it was impossible to locate a fuel valve centrally in the combustion chamber. The fuel-injection valve used with this combustion chamber was spring-loaded and fitted with an impact surface for producing a flat, fan-shaped spray. The fuel was injected from a point near the periphery of the combustion chamber. This cylinder head was tested with a standard Navy type Liberty piston and a compression ratio of 12.7.

CYLINDER HEAD NO. 2

Figure 4 shows the outline of the first type of combustion chamber used having a bulb-type precombustion chamber. The connecting orifice between the bulb and cylinder was 1 inch in diameter. This cylinder head was fitted with a standard Army type Liberty piston arranged to give a compression ratio of 9.9. The fuel system comprised an automatic diaphragm-type fuel-injection valve and an eccentric-driven fuel injection pump.

FIG. 3.—Fuel-injection performance, Liberty test engine. Combustion chamber No. 1, having directed flow of inlet air. Maximum explosion pressure 800 pounds gauge, 1,500 R. P. M.

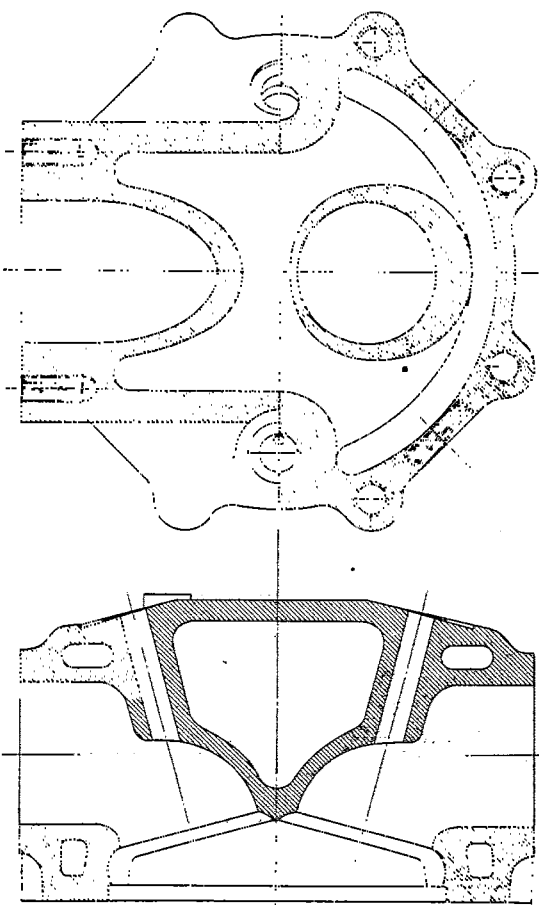
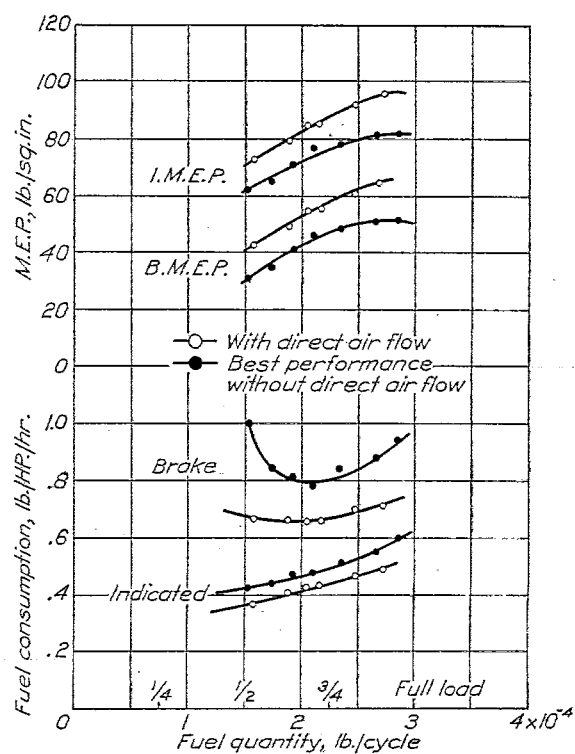


FIG. 2.—Combustion chamber design No. 1

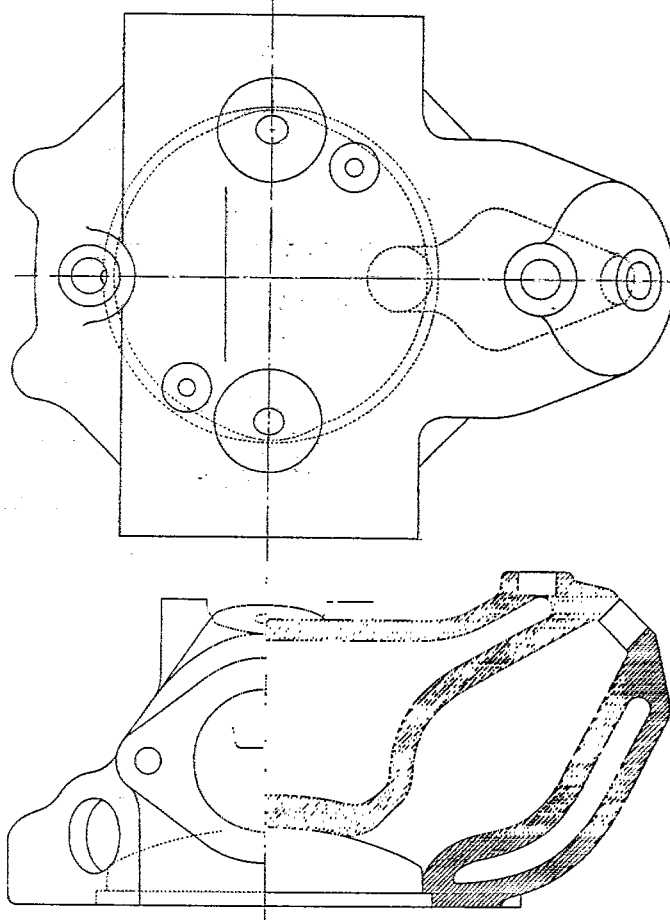


FIG. 4.—Combustion chamber design No. 2

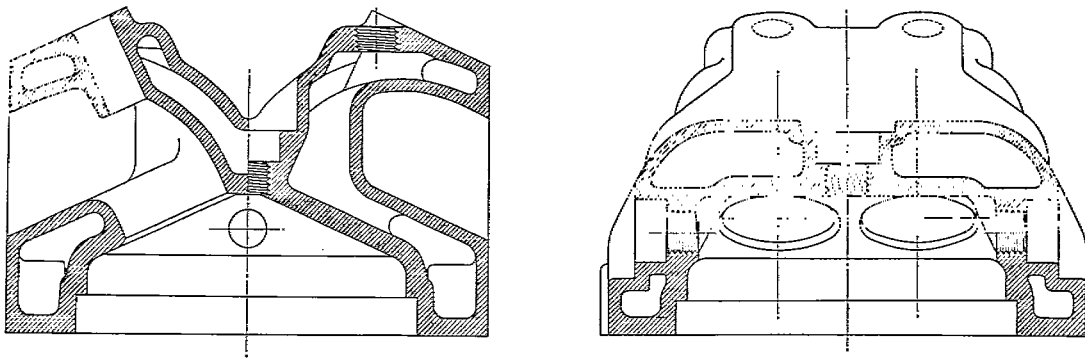


FIG. 6.—Combustion chamber of Universal test engine

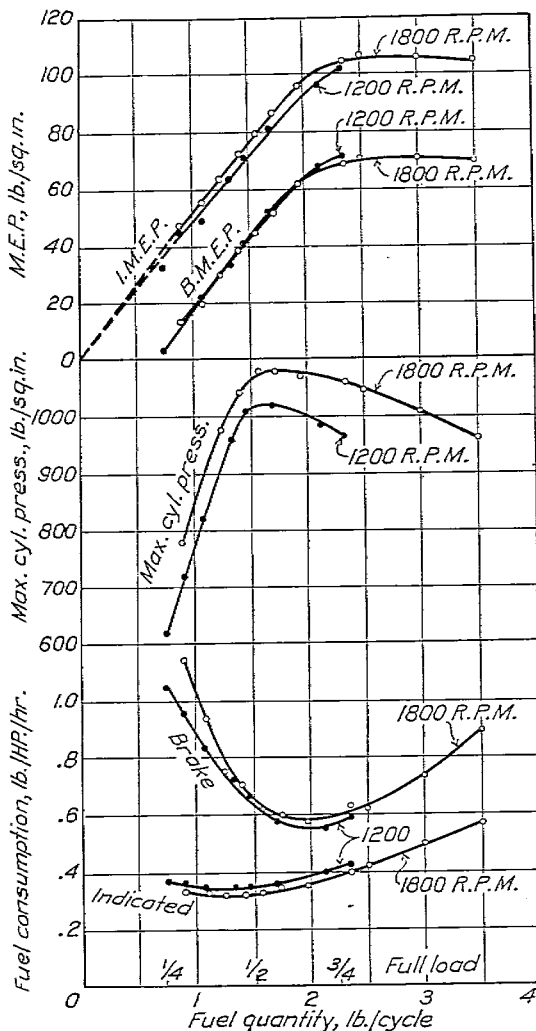


FIG. 5.—Effect of load on engine performance. Fuel-injection performance, cylinder head No. 2. Orifice, 1 inch; engine, S. C.-L. T. E.; compression ratio, 9.9; operating temperature, standard

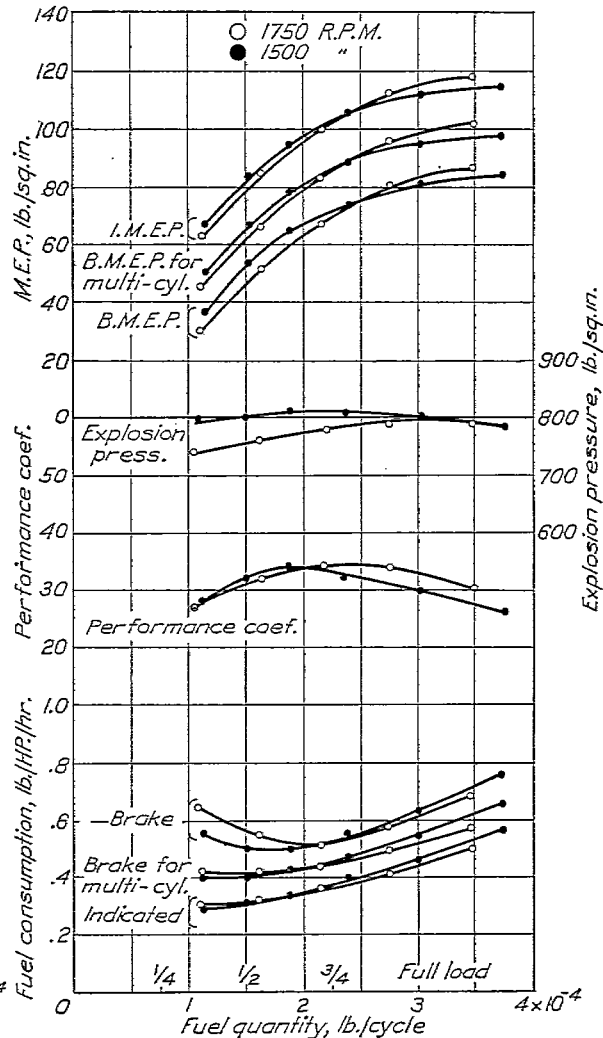


FIG. 7.—Fuel-injection performance, Universal test engine

CYLINDER HEAD OF UNIVERSAL TEST ENGINE

The type of combustion chamber shown in Figure 6 was designed for carburetor work on the N. A. C. A. Universal test engine. (Reference 5.) The cylinder head was tested using a diaphragm-type fuel-injection valve and an eccentric-driven fuel injection pump. The piston used was an Army type Liberty piston. The compression ratio of this engine was adjusted for the tests reported at 10.2.

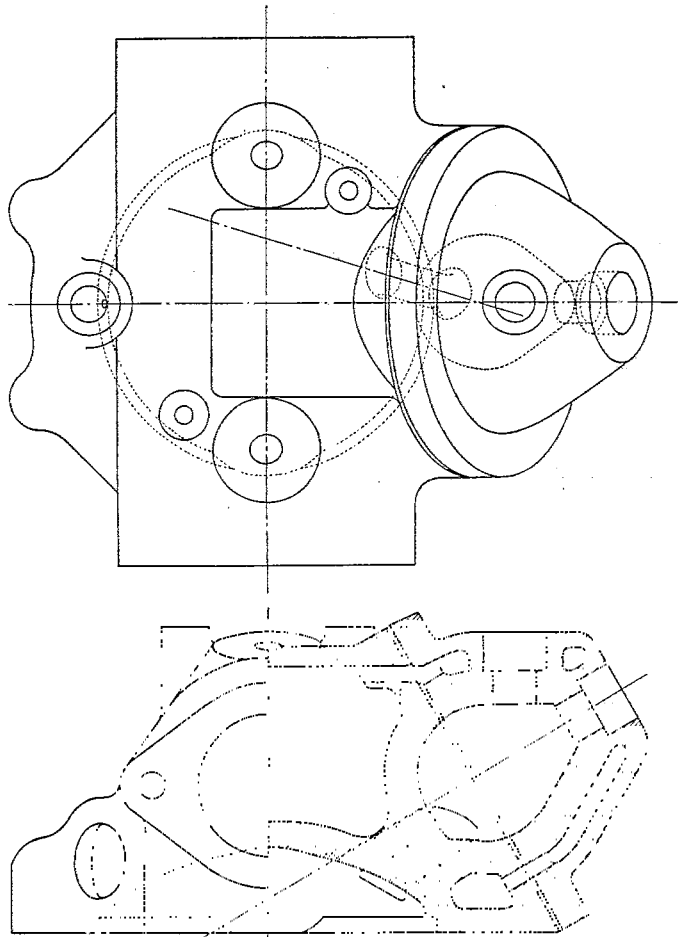


FIG. 8.—Combustion chamber design No. 3

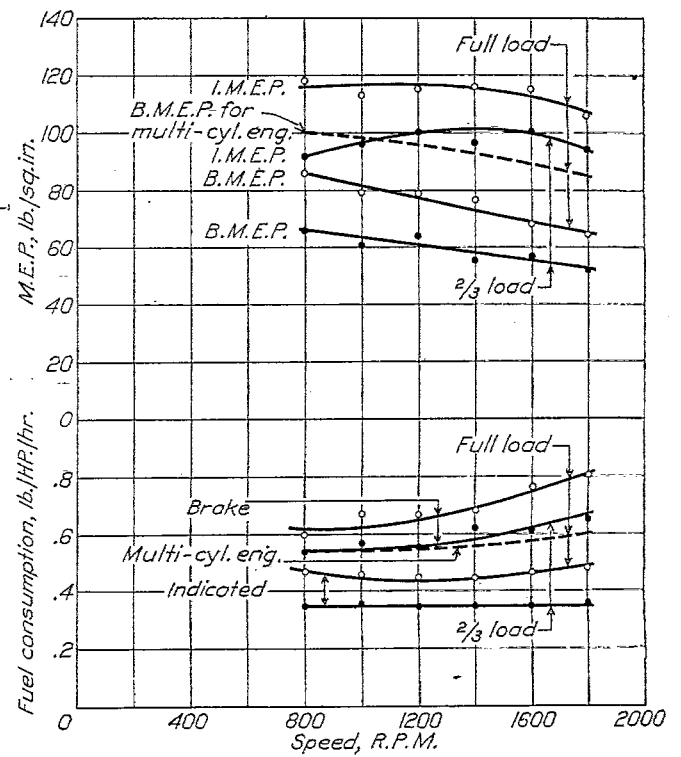


FIG. 10.—Fuel injection performance, Liberty test engine. Cylinder head No. 3

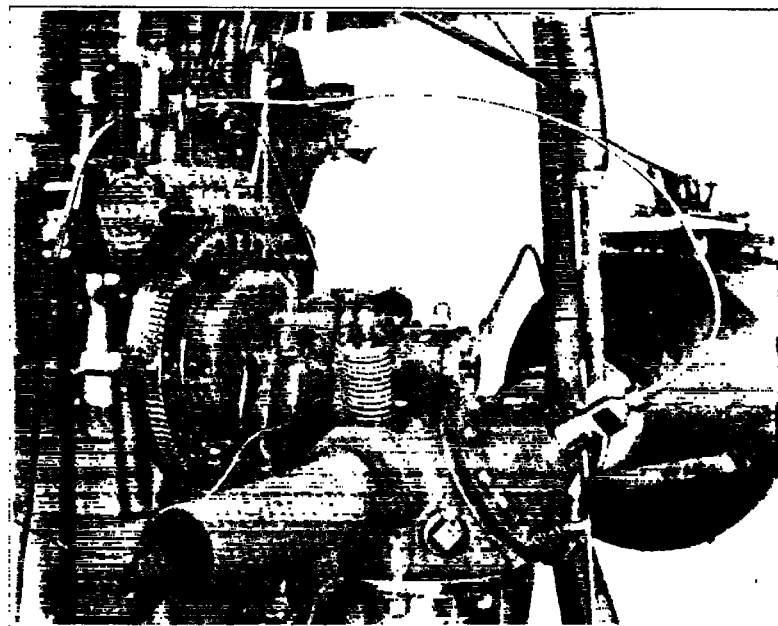


FIG. 9.—Cylinder head No. 3 assembled on Liberty test engine

CYLINDER HEAD NO. 3

The combustion chamber illustrated in Figures 8 and 9 was designed to give a high degree of turbulence within the pear-shaped bulb on the compression stroke and within the cylinder on the expansion stroke. This has been obtained by locating the $\frac{3}{16}$ -inch orifice to produce tangential air flow in both the bulb and cylinder. The ratio of the volume of air in the bulb to the volume of air in the cylinder is approximately one when the piston is on top center.

In order to determine the effects of variations in the degree of cylinder air turbulence on engine performance, provision was made in the design for progressively altering the orifice. The cylinder head has been tested with a $\frac{3}{16}$ -inch sharp-edge orifice, with the orifice edges rounded, and the orifice flared to discharge the burning gases from the bulb tangentially over one-half the piston area. The compression ratio used for the tests reported was 13.5 to 1, which gave a compression pressure of 450 pounds per square inch at 1,000 R. P. M.

PERFORMANCE MEASUREMENTS

FUEL

The fuel used in these tests was a commercial grade of Diesel-engine fuel oil having a Saybolt viscosity of 41 seconds and a specific gravity of 0.85 at 80° F.

ENGINE POWER

The engine power was determined by means of torque scales graduated to read in 0.2 pound intervals and a magnetically operated stop watch and counter.

The fuel consumption was determined by timing the flow of 200 cubic centimeters of fuel with a stop watch. The quantity of fuel delivered per cycle by the injection pump for any given pump adjustment was determined from the total number of engine cycles passed through during the consumption of the 200 cubic centimeters of fuel.

MAXIMUM CYLINDER PRESSURES

Maximum cylinder pressures have been determined by a gas balanced-valve type pressure indicator. This has been replaced, however, by a diaphragm-type indicator which is operated by the pressure of the gases within the engine cylinder. The pressure of the cylinder gases, trapped above the diaphragm, is indicated by a calibrated pressure gauge. Since the weight of the moving element of the indicator is 0.00044 pound, the exposed area 0.0767 square inch, the maximum lift 0.002 inch, and the seat width 0.005 inch, the error in the pressures recorded is probably small. Engine tests have shown that it is unnecessary to provide means for cooling the diaphragm of this type of maximum cylinder pressure indicator.

ENGINE PERFORMANCE AND DISCUSSION

CYLINDER HEAD NO. 1

The performance of cylinder head No. 1 was an improvement over that obtained with a standard Liberty aircraft engine cylinder and a special piston. (Reference 7.) The operation of the engine was smoother and no trouble was experienced with cracking of the standard aircraft aluminum pistons.

An improvement in combustion was obtained by directing the flow of the inlet air through the inlet valve to produce a definite kind of air flow within the cylinder. (Reference 8.) The curves of Figure 3 give the performance of this combustion chamber with and without directed air flow. It may be noted that in these tests the I. M. E. P. was increased from 82.0 to 96.0 pounds per square inch, with a corresponding decrease in the fuel consumption from 0.60 to 0.51 pound per I. HP. per hour. This increase in performance, obtained by directing the flow of the inlet air toward the fuel-injection valve, was thought to be caused by the better removal of the products of combustion surrounding the fuel valve. The fuel, therefore, was injected into a charge of relatively pure air, which improved the combustion.

CYLINDER HEAD NO. 2

The performance of cylinder head No. 2 for various loads and for speeds of 1,200 and 1,800 R. P. M. is shown in Figure 5. The B. M. E. P. at full load and 1,800 R. P. M. is 71.0 pounds per square inch. The full-load fuel quantity is considered as the fuel weight per cycle giving 15 per cent excess air. The corresponding I. M. E. P. is 106.0 pounds per square inch. This large difference in mean effective pressure is caused by the low mechanical efficiency of this single-

cylinder test engine. If a mechanical efficiency of 80 per cent is assumed as an average value for multiple-cylinder oil engines, the B. M. E. P. is increased to 84.8 pounds per square inch. This same factor of mechanical efficiency is responsible for the high fuel consumption when taken on a brake-horsepower basis. The linear portions of the I. M. E. P. and B. M. E. P. curves indicate that for fuel quantities less than 0.0002 pound per cycle combustion of the fuel is practically complete. For fuel quantities greater than this, however, the curves tend to flatten, which indicates that the fuel and air are not sufficiently well mixed to obtain efficient combustion. Data for the curve of maximum explosion pressures were obtained with a gas balanced-valve type of maximum explosion pressure indicator.

CYLINDER HEAD OF UNIVERSAL TEST ENGINE

The engine performance obtained with the Universal test engine for variable fuel quantity and speeds of 1,500 and 1,750 R. P. M. is shown in Figure 7. Due to the pent-roof type combustion chamber, it was impossible to distribute the fuel completely with a centrally located diaphragm-type injection valve. The results are of interest since they show the engine performance obtained with a design of combustion chamber unsuitable for fuel injection but with a fuel valve and pump designed to give a high degree of fuel atomization. This engine, due to its construction (Reference 5), has a higher mechanical efficiency than the Liberty test engine, which accounts, in part, for the higher B. M. E. P.

CYLINDER HEAD NO. 3

The curves in Figure 10 give the engine performance of cylinder head No. 3 with a sharp-edge orifice for the range of speeds from 800 to 1,800 R. P. M. and for two-thirds and full load.

The maximum value of 117.0 pounds per square inch I. M. E. P. is at 1,200 R. P. M. and full load. The fuel economy is 0.44 pound per I. HP. per hour. The corresponding B. M. E. P. values are 77.0 pounds per square inch and 0.65 pound per B. HP. per hour. If a mechanical efficiency of 80 per cent is assumed, as shown by the curve "Multicylinder engine," the performance values on a brake basis are, respectively, 96.0 pounds per square inch B. M. E. P. and 0.55 pound per B. HP. per hour. For two-thirds load the indicated fuel consumption curve has the average value, throughout the range of speeds, of 0.35 pound per I. HP. per hour.

The improvement in engine performance obtained by rounding the orifice edges is indicated in the curves of Figure 11. It may be noted that the I. M. E. P. at full load, 3×10^{-4} pound per cycle, was increased approximately 4.5 per cent by this alteration to the orifice. The maximum cylinder pressures as recorded with the diaphragm-type maximum cylinder pressure indicator were maintained constant for both series of tests. At a fuel quantity of 3.5×10^{-4} pound per cycle and zero per cent excess air, the maximum cylinder pressure was 755 pounds per square inch.

The engine performance coefficient, which is taken as the ratio

$$\frac{\text{I. M. E. P.}}{\text{cyl. pressure} \times \text{fuel consumption lb./I. HP./hr.}},$$

has a maximum value of 49.0 at a fuel quantity of 1.5×10^{-4} pound per cycle, which corresponds to approximately 130 per cent excess air in the cylinder. As the fuel quantity is increased above this value the performance coefficient decreases rapidly because of the decrease in the combustion efficiency of the combustion chamber.

After the edges of the orifice had been rounded the orifice on the cylinder side was flared to discharge the gases from the bulb tangentially over one-half the piston area. The curves in Figure 12 give the engine performances for this alteration to the orifice. The full-load I. M. E. P. was increased to 119 pounds per square inch, and the corresponding B. M. E. P. to 76 pounds per square inch. The low value of the mechanical efficiency, 63.8 per cent, accounts for the wide difference in values of the I. M. E. P. and B. M. E. P. curves. The fuel consumption, taken on an I. HP. basis, varies from 0.26 to 0.43 pound per HP. per hour for one-fourth to full-load fuel quantities, respectively. Flaring the orifice has not appreciably increased the maximum value of the performance coefficient over that shown in Figure 11, but the maximum value now appears at two-thirds load instead of one-half load, the corresponding percentages of excess air within the cylinder being approximately 72 and 132 per cent. This would indicate that flaring the orifice permitted the fuel from the bulb to reach more of the air in the cylinder.

The fuel consumption of 0.26 pound per I. H.P. per hour at one-fourth load, one-fourth the fuel weight per cycle at full load, is worthy of note for an engine speed of 1,600 R. P. M.

Figure 13 shows the variation of engine performance with the bulb-to-cylinder orifice flared as noted above for speeds from 600 to 1,800 R. P. M. and for a constant fuel quantity of 2.5×10^{-4} pounds per cycle, which is approximately 83 per cent of the full-load fuel charge. The I. M. E. P. throughout the entire range of speeds is approximately 110 pounds per square inch and the fuel economy 0.39 pound per I. H.P. per hour. The curves of F. M. E. P. (motoring) plotted against speed show the large difference between the indicated and brake power of this engine.

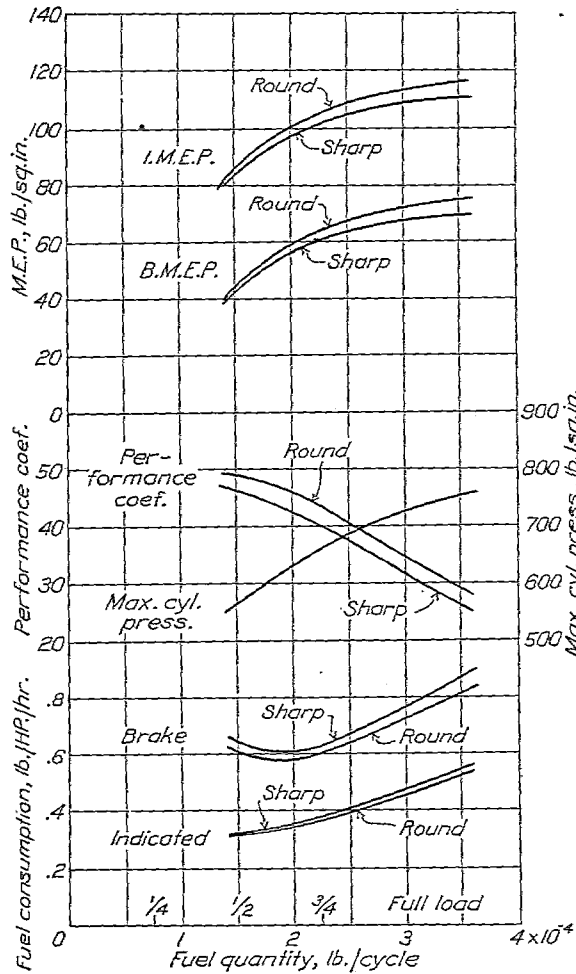


FIG. 11.—Comparison of sharp and rounded orifice edges. Engine, L.T.E. Cylinder head No. 3; engine parts, standard; compression ratio, 13.5; engine R. P. M., 1,600; operating temperature, standard; injection valve No. 3A-048; injection pump No. 5.

POSITION OF FUEL-VALVE NOZZLE

The effect on engine performance of extending the fuel nozzle into the bulb for distances of $\frac{1}{4}$ inch and $\frac{1}{2}$ inch has been determined for the full range of fuel quantities per cycle and a speed of 1,600 R. P. M. The tests indicate that the flush or $\frac{1}{4}$ -inch extension gave somewhat better performance than the $\frac{1}{2}$ -inch extension. An examination of the carbon deposits on the walls of the bulb after each engine test indicate that for the flush and $\frac{1}{4}$ -inch extensions part of the fuel was swept from the nozzle and thrown against the walls of the bulb. The $\frac{1}{2}$ -inch extension gave a uniform coat of carbon over the entire surface of the bulb. The engine performance data, however, showed that these short extensions did not result in any appreciable gain in combustion efficiency.

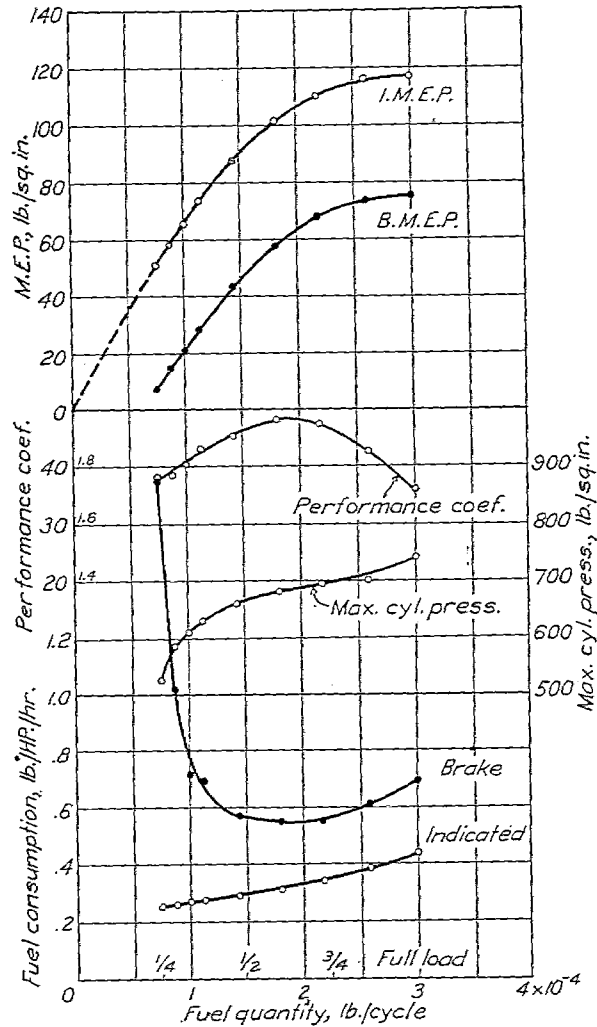


FIG. 12.—Effect of load on engine performance. Fuel-injection performance, cylinder head No. 3. Engine S. C.-L. T. E.; orifice, $\frac{1}{4}$ -inch; orifice flared to cover one-half piston area; compression ratio, 13.5; operating temperature, standard; static opening pressure, 6,000 lb./sq. in.; fuel, Diesel oil, sp. gr. = 0.847

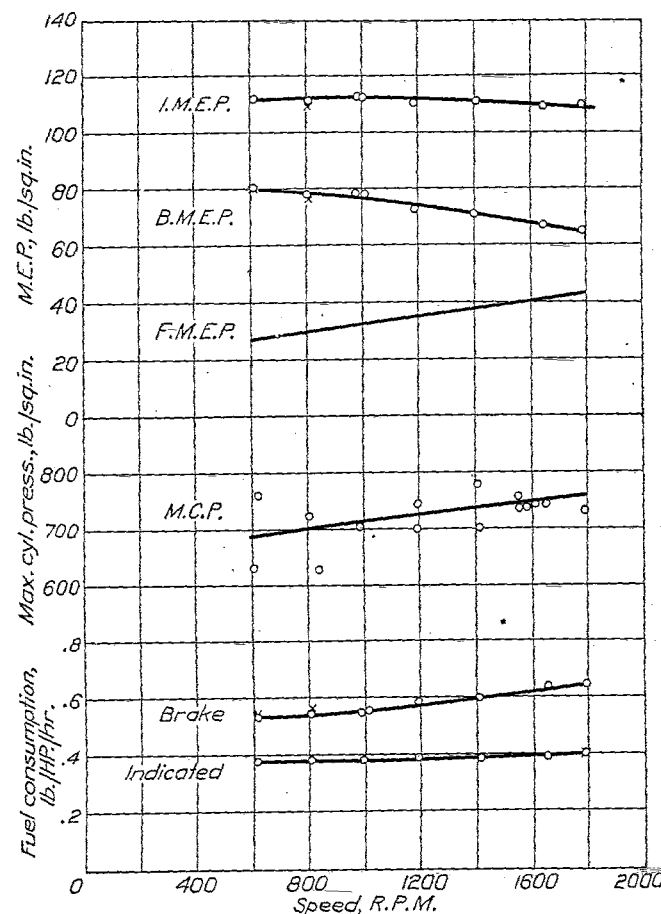


Fig. 13.—Effect of speed on engine performance. Engine, S. C. Liberty. Compression ratio, 13.5; operating temperature, standard; engine parts, standard; fuel, lb./cycle, 2.50×10^{-4} .

CONCLUSIONS

Comparison of the data presented shows that the precombustion chamber type cylinder head, arranged to provide controlled, high-velocity air turbulence as in cylinder head No. 3, gave the best engine performance. It is concluded that this type of cylinder head gave the highest indicated mean effective pressures and the lowest fuel consumptions per indicated horsepower hour with the lowest cylinder pressures at all loads and speeds in these tests, because the most thorough mixing of the fuel and air was obtained and high cylinder pressures were prevented by this cylinder head design.

Equal and even superior engine performance have been obtained with integral combustion chamber type cylinder heads, but the cylinder pressures were in excess of those for the precombustion chamber type cylinder head.

These tests indicate that improvement in the performance of aircraft oil engines depends primarily upon the complete mixing of well-atomized fuel with the air charge in precombustion chamber type cylinder heads and, in addition, upon the prompt ignition of the fuel in integral combustion chamber type cylinder heads.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., June 9, 1927.

REFERENCES

1. JOACHIM, WILLIAM F.: Oil Spray Investigation of the National Advisory Committee for Aeronautics. Paper presented before the Oil Power Conference at Pennsylvania State College, Pa., April 24, 1927.
2. JOACHIM, WILLIAM F.: Research on Oil Injection Engines for Aircraft. "Mechanical Engineering," November, 1926.
3. BEARDSLEY, E. G.: The N. A. C. A. Fuel Spray Photography Apparatus and Test Results from Several Researches. N. A. C. A. Technical Report No. 274 (1927).
4. BEARDSLEY, E. G.: Some Factors Affecting the Reproducibility of Penetration and the Cut-Off of Oil Sprays for Fuel Injection Engines. N. A. C. A. Technical Report No. 258 (1927).
5. WARE, MARSDEN: Description of the N. A. C. A. Universal Test Engine and Some Test Results. N. A. C. A. Technical Report No. 250 (1927).
6. PATON, C. R., and KEMPER, CARLTON: Power Output and Air Requirements of a Two-Stroke Cycle Engine. N. A. C. A. Technical Report No. 239 (1926).
7. GARDINER, A. W.: A Preliminary Study of Fuel Injection and Compression Ignition as Applied to an Aircraft Engine Cylinder. N. A. C. A. Technical Report No. 243 (1926).
8. KEMPER, CARLTON: Improving the Performance of a Compression Ignition Engine by Directing Flow of the Inlet Air. N. A. C. A. Technical Note No. 242 (July, 1926).